# Electrified Aircraft Propulsion Flight Project Battery Industry Day

November 30, 2020

Virtual Meeting

**Accelerate transition of 1MW class powertrain systems to US transport aircraft fleet**

# Agenda

| Start | End | Session | Speaker |
|---|---|---|---|
| 10:00 AM | 10:05 AM | Welcome | Gaudy Bezos-O'Connor |
| 10:05 AM | 10:20 AM | NASA Intro | Ralph Jansen |
| 10:20 AM | 10:40 AM | NASA Battery Intro | Ajay Misra |
| 10:40 AM | 11:00 AM | Q&A | |
| 11:00 AM | 11:15 AM | Break | |
| 11:15 AM | 11:30 AM | Aircraft 1 | Ampaire |
| 11:30 AM | 11:45 AM | Aircraft 2 | Boeing |
| 11:45 AM | 12:00 PM | Aircraft 3 | Wright Electric |
| 12:00 PM | 12:30 PM | Lunch 1 (East Coast) | |
| 12:30 PM | 12:45 PM | Battery 1 | Amprius |
| 12:45 PM | 1:00 PM | Battery 2 | CRG/Lectratek |
| 1:00 PM | 1:15 PM | Battery 3 | Cuberg |
| 1:15 PM | 1:30 PM | Battery 4 | Eagle Picher |
| 1:30 PM | 1:45 PM | Break | |
| 1:45 PM | 2:00 PM | Battery 5 | EP Systems |
| 2:00 PM | 2:15 PM | Battery 6 | Navitas |
| 2:15 PM | 2:30 PM | Battery 7 | Sion Power |
| 2:30 PM | 2:45 PM | Battery 8 | Solid Power |
| 2:45 PM | 3:30 PM | Lunch 2 (West Coast) | |
| 3:30 PM | 3:45 PM | Battery 9 | Teledyne |
| 3:45 PM | 4:00 PM | Battery 10 | GLX Power |
| 4:00 PM | 4:15 PM | Battery 11 | Ionic Materials |
| 4:15 PM | 4:30 PM | Battery 12 | Mobius Energy |
| 4:30 PM | 4:45 PM | Break | |
| 4:45 PM | 5:00 PM | Battery 13 | Ford |
| 5:00 PM | 5:15 PM | Battery 14 | Romeo Power |
| 5:15 PM | 5:30 PM | Battery 15 | General Atomics |
| 5:30 PM | 5:45 PM | Battery 16 | Lavle |
| 5:45 PM | 6:00 PM | Closing Remarks | |

# Why is Electrified Propulsion important?

- **EP enables favorable direct operating cost (DOC) trades**
  - Total Energy
  - Maintenance
- **EP creates a flexible design space opportunities**
  - Boundary layer ingestion
  - Distributed architectures
  - Reduced turbofan core sizes
- **EP coupled with advanced airframe architectures**
  - May enable functionally silent and ultra low emission flight
- **EP is synergistic with low emission airport infrastructure changes**

**5-year EPFD Project start in FY21**

# Agency and ARMD Strategic Plan Flow Down to EPFD Project

**Agency Goal**

**3.0 Address national challenges and catalyze economic growth**
3.2: Transform Aviation Through Revolutionary Technology Research, **Development, and Transfer**

**AERONAUTICS STRATEGIC THRUST**

**Thrust 3: Ultra Efficient Subsonic Transports**
Realize revolutionary improvements in economics and environmental performance for subsonic transports with opportunities to transition to alternative propulsion and energy

**AAVP and IASP CRITICAL COMMITMENT**

**Critical Commitment 3.1** - Demonstrate **practical vehicle-level integration of MW-class electrified aircraft propulsion** systems, leveraging advanced airframe systems to **reinvigorate the regional and emerging smaller aircraft markets and strengthen the single-aisle aircraft market**.

**Technical Challenges**

**TC 5.2:** Establish viable concept for 5-10 MW hybrid gas-electric propulsion system for a single-aisle class vehicle with reduced fuel burn, emissions and noise (TRL2) Finished in FY19
**(AATT)**

**TC 10.1:** Demonstrate representative hybrid electric powertrain having a total power of at least 3X the state-of-the-art that meets fault management, redundancy, and power quality requirements (TRL 4) and develop key components to TRL 6.
**(AATT with EPFD Enhancements)**

**TC 14.1**: Achieve 20% power extraction at altitude from a modern commercial turbofan engine with the thrust, efficiency, operability, and durability to enable the benefits of electrified aircraft propulsion at a vehicle level.
**(AATT with EPFD Enhancements)**

# EPFD Approach

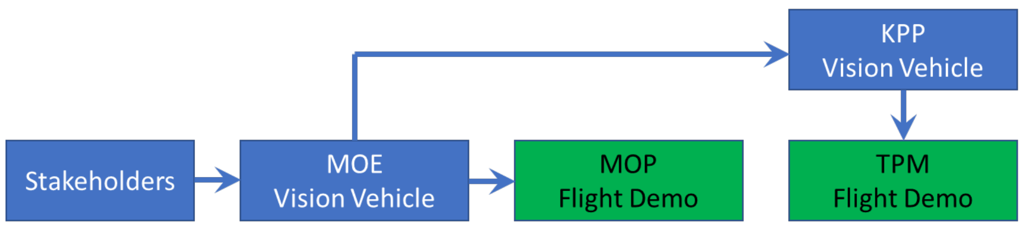
- **Accelerate US industry technology readiness of integrated MW-class electrified powertrain systems**
  - Facilitate jump to new aviation industry S – curve by focusing on integrated MW-class powertrain system technology
  - Focus on next generation single aisle (150 – 200 passenger seat class) commercial transport aircraft
  - Ensure an appropriate mix of potentially disruptive concepts and commercial transport products
    - Commercial thin haul transport transport aircraft can potentially disrupt hub and spoke system
  - Directly engage propulsion companies to facilitate timely integrated MW-class powertrain system development and transition
- **Plan and Conduct at least two integrated MW-class powertrain system flight demonstration**
  - Identify and address regulation and standards gaps
  - Identify and retire barrier technical and integration risks
- **Employ right-sized project management and procurement rigor for efficient execution and timely funding expenditures:** highly leveraging industry processes and practices with significant NASA insight to make informed decisions at periodic reviews
- **Coordinate closely with ARMD programs to fully leverage prior and ongoing ARMD electrified powertrain system investments**

# Objectives of Battery Industry Day

- Connect U.S. aircraft and propulsion companies with U.S. battery companies with interest in MW class Electrified Aircraft Propulsion
- Provide awareness of upcoming Electrified Aircraft Propulsion Project Request for Proposals and related project performance objectives
- Provide awareness of battery challenges for MW class Electrified Aircraft Propulsion
- Provide summary of NASA-DOE workshops related to battery technologies for electrified aircraft

# Formulation Studies

- **Study contracts have been completed with six companies to define:**
  - The largest market opportunities for MW-Class EAP
  - A Vision Vehicle (potential product) for that market
  - Barrier Technical Risks that need to be overcome for the Vision Vehicle
  - Technology maturation needed for Vision Vehicle
  - A proposed flight demonstration to reduce the Barrier Technical Risks and increase the Technology Readiness levels for Integrated MW-class powertrain systems
  - Probabilistic assessments of cost and schedule for the proposed flight demonstration




Formulation studies informed the objectives and performance goals of the Electrified Powertrain Flight Demonstration project

# Technical Measures of Effectiveness

- **The EPFD project has established a draft set of Technical Measures of Effectiveness**

| MOE # | Measure of Effectiveness (MOE) |
|---|---|
| MOE-1 | Establish at least two Vision Vehicles that address the single-aisle, regional, or thin haul markets. |
| MOE-2 | Define a viable path that accelerates U.S. Industry product introduction of the Vision Vehicle and execute the part of the path that requires government participation. |
| MOE-3 | Identify and reduce Barrier Technical Risks to the introduction of the Vision Vehicle through ground and flight tests. |
| MOE-4 | Reduce regulations and standards barriers to the introduction of Vision Vehicles with Integrated MW-Class Powertrain Systems into the air fleet. |
| MOE-5 | Collect the data defined in the Data and Intellectual Property Management (DIPM) plan to verify Key Performance Parameters and support regulations and standards work. |

# KPPs and TPMs

- **Draft Key Performance Parameters for the Vision Vehicle and draft Technical Performance Parameters for the flight demonstration have been established.**

| Key Performance Parameter (KPP)# | Key Performance Parameter (KPP) | Full Success<br>Single Aisle Part 25 | Minimum Success<br>19 PAX Thin Haul Part 23 |
|---|---|---|---|
| KPP-1 | Total Power level of the Integrated MW-Class Powertrain System | 2MW | 500kW |
| KPP-2 | Power Level of individual electrical components | 1MW | 250kW |
| KPP-3 | Operating Voltage of the Integrated MW-Class Powertrain System | 1000V | 500V |
| KPP-4 | Altitude Capability of the Integrated MW-Class Powertrain System | 40,000 ft. | 20,000 ft. |
| KPP-5 | Specific Power of the Integrated MW-Class Powertrain System | 1.25 kW/kg | 0.5 kW/kg |
| KPP-6 | End to End loss of the Integrated MW-Class Powertrain System | 20% | |
| KPP-7 | Mission Fuel Burn/Energy Reduction | 4% for Part 25 Transport Aircraft | 10% for Part 23 Transport Aircraft |

| Technical Performance Parameter (TPM)# | Technical Performance Parameter (TPM) | Full Success | Minimum Success |
|---|---|---|---|
| TPM-1 | Total Power level of the Integrated MW-Class Powertrain System | 1.5MW | 500kW |
| TPM-2 | Power level of individual electrical components | 1MW | 250kW |
| TPM-3 | Operating Voltage of the Integrated MW-Class Powertrain System | 1000V | 500V |
| TPM-4 | Altitude Capability of the Integrated MW-Class Powertrain System | 30,000 ft. | 15,000 ft. |
| TPM-5 | Specific Power of the Integrated MW-Class Powertrain System | 1.25 kW/kg | 0.5 kW/kg |
| TPM-6 | End to End loss of the Integrated MW-Class Powertrain System | 20% | 25% |

# Barrier Technical Risks

- **Barrier Risks**
  - Overarching risks applicable to future commercial transport applications by US Industry that the project will reduce over the life of the project
- **Six Barrier Technical Risks have been identified.**
- **The EPFD project intends to reduce these barrier technical risks to EAP Vision Vehicles through the execution of two or more U.S. Industry flight demonstration of integrated MW-class powertrains.**
- **Battery performance and airworthiness is one of the six barrier risks. The industry day is being held to foster connections between battery suppliers and aircraft and propulsion companies.**

| Risk ID | Risk Title | Statement | Project Specific Risk |
|---|---|---|---|
| EPFD-028 | Barrier Risk- Battery System Performance Shortfall | Given that the battery pack requirement exceeds current state of the art technology, there is a possibility that the battery system design does not meet performance requirements, resulting in a decrease in time per flight, increasing the total number of flight tests needed, impacting the cost and schedule. | EPFD-039: Battery Airworthiness |

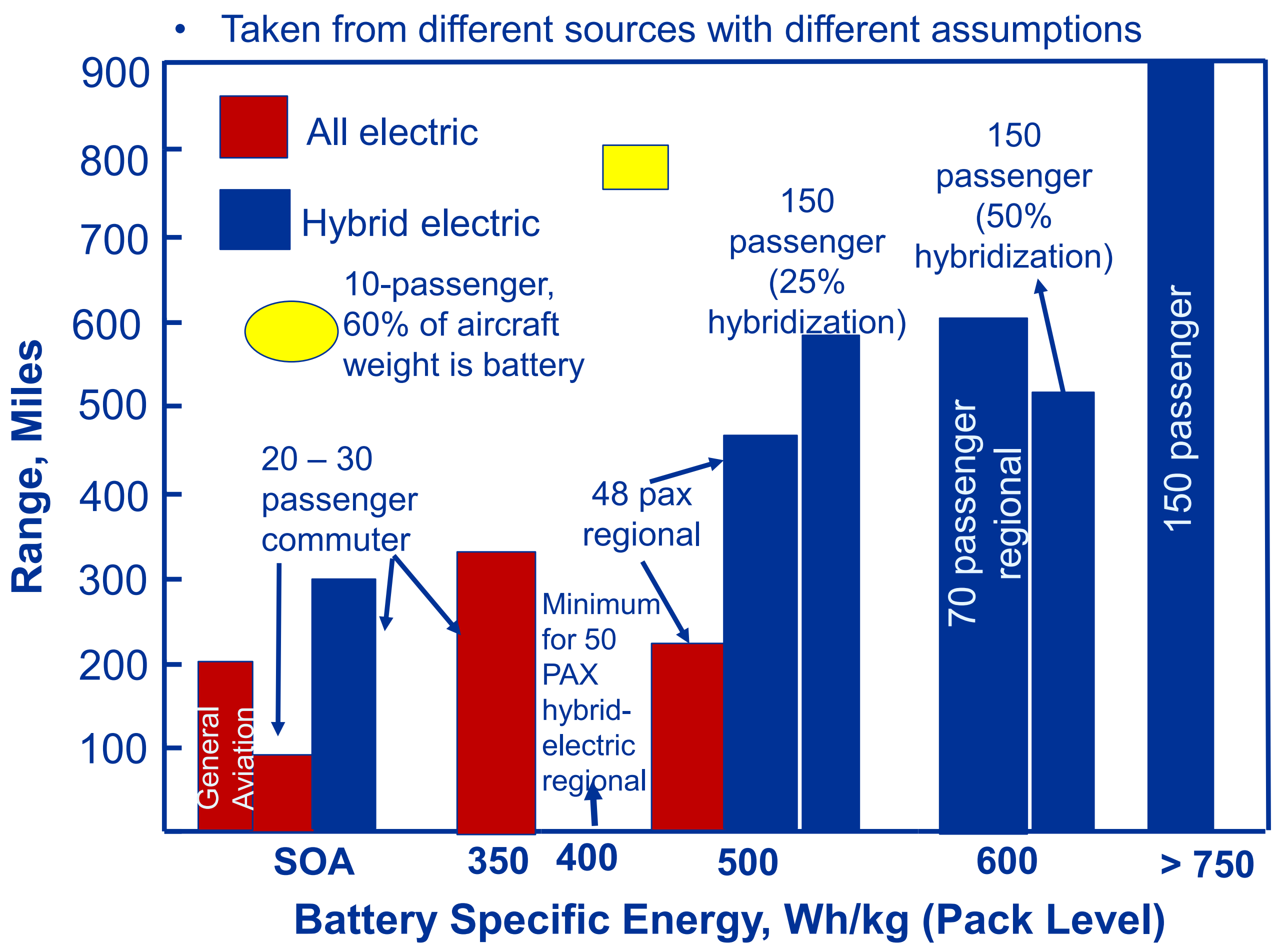
# EPFD Draft Request for Proposals has been posted

- **Draft Request for Proposal has been posted.**
  - Link: https://beta.sam.gov/opp/09c460e4b5b14e22b43c4b60ae4010dc/view?keywords=80afrc21r0009&sort=-relevance&index=&is_active=true&page=1
- **Description**
  - Attached is the DRAFT Request for Proposal (DRFP) for the Electrified Powertrain Flight Demonstration. The objective of this requirement is to plan, manage, and conduct appropriate ground tests and flight tests of an integrated MW-class Powertrain System that enables the offeror's vision system, that meets the described needs, goals and objectives identified in the attached Statement of Objectives, and that are in alignment with system and data requirements defined in the System Requirements Document (SRD) and Data Requirements Document (DRD). See the attached Statement of Objectives for additional information. The DRDs and SRD will be provided via an amendment to this DRFP. Potential Offerors shall monitor bata.SAM.gov for amendments to this DRFP.
  - Potential Offerors are encouraged to review all aspects of the DRFP, including the requirements, schedules, proposal instructions, and evaluation approaches. Potential Offerors should provide questions and/or comments and identify any unnecessary or inefficient requirements relating to the DRFP no later than 2:00 pm Pacific, Dec 16, 2020.
  - An Industry Day will be held Dec 10, 2020. A registration link for the Industry Day will be provided.

# Battery Technology for MW Class Electrified Aircraft Propulsion

Dr. Ajay Misra (NASA)

# Battery Specific Energy Requirement for Conventional Takeoff and Landing Electrified Aircraft

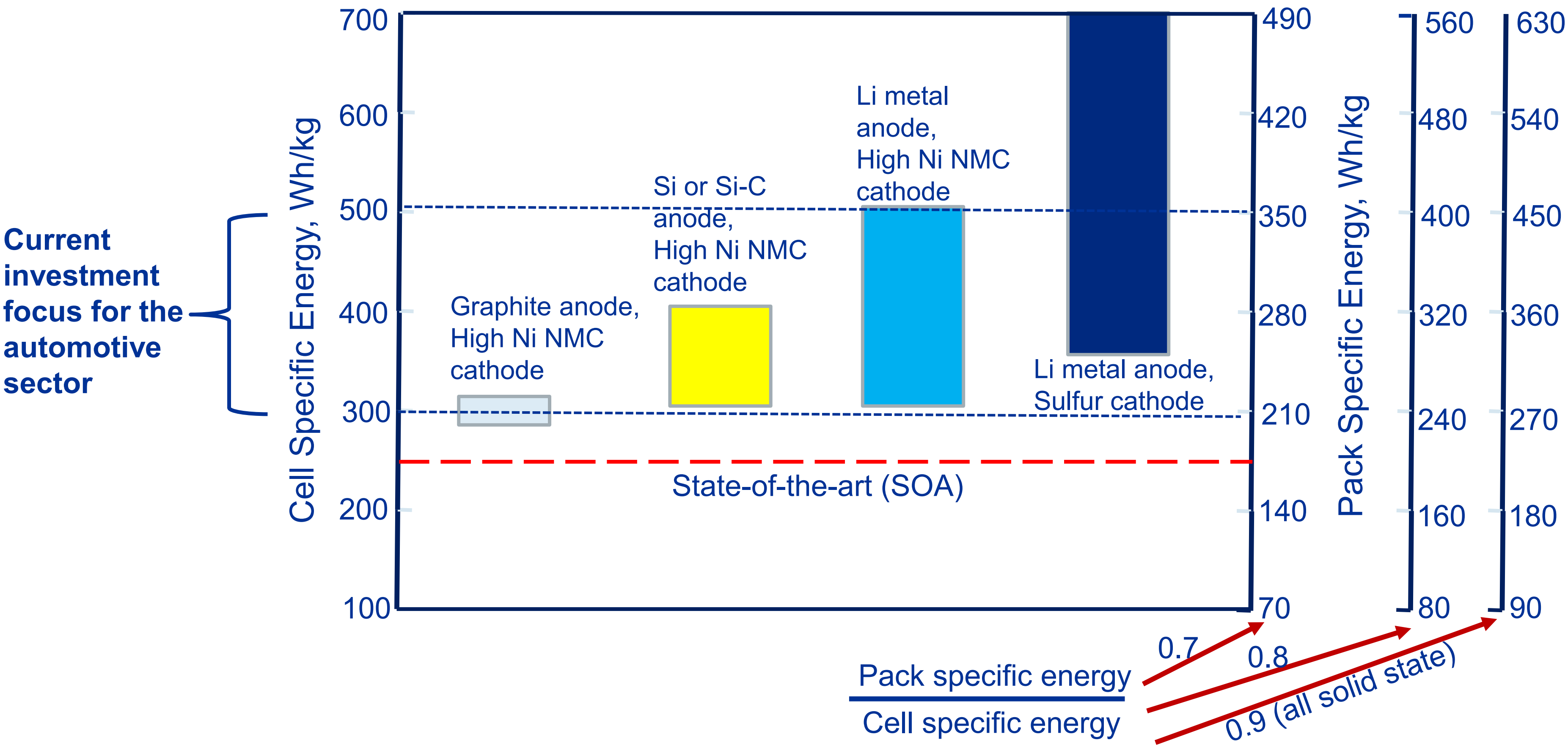



- Battery requirement is a function of degree of hybridization
- Potential hybrid electric short flight (300 – 400 miles) opportunities for large regional and 150 Passenger single aisle with 400 – 500 Wh/kg pack specific energy
- For hybrid electric large aircraft with battery used during takeoff only:
  - 300 Wh/kg pack specific energy for 30-50 passenger aircraft
  - >400 Wh/kg pack specific energy for single-aisle 150 passenger aircraft

# Evolution of Electrified Aircraft Market with Improvements in Battery Technology

| Battery Pack Specific Energy | Potential Missions | Potential Market Introduction |
|---|---|---|
| SOA (150 – 170 Wh/kg) |     | Initial commercial introduction possible for all-electric with limited range and payload, extended capability with hybrid-electric |
| 300 Wh/kg |   | All-electric eVTOL urban air mobility with 4 passenger and 50+ mile range; 20-passenger all-electric commuter |
| 400 Wh/kg<br>Sweet spot for many applications |     | Desired capability for all-electric eVTOL urban air mobility, long-range all-electric commuter, Initial version of small hybrid-electric regional |
| 500 Wh/kg |   | Expansion to various classes of hybrid-electric regional aircraft, short-range 150 Passenger, single aisle hybrid-electric aircraft |
| > 700 Wh/kg |   | Single aisle, 150 passenger single-aisle aircraft, long range |

# Progression of Specific Energy of Advanced Li Batteries



# Comparison of C-Rating and Power Density of Electric Vehicles and Electric Aircraft

| | Electric Vehicles | Electric Aircraft |
|---|---|---|
| C-rating (burst) | 3to 4 for a few seconds | 2 to 5 or higher during takeoff and climb and vertical lift/hover, could last for several minutes for many missions |
| C-rating (steady cruise) | 0.5 or lower | Could be 1 and higher depending on mission and speed |
| Specific power | 0.4 – 0.5 kW/kg | 1- 2 kW/kg for many missions |

# Notional Timeline for Evolution of Battery Technology

| Timeframe | Pack Specific Energy (Wh/kg) | Likely Chemistry |
|---|---|---|
| Present | 150 - 170 | |
| 2022 - 23 | 215 | Current anode, Adv. NMC cathode, maybe single crystal NMC , liquid electrolyte |
| 2025 | 250 - 300 | Si or Si/C anode, Adv. NMC cathode (including single crystal), liquid electrolyte |
| 2030 | 300 - 350 | Li metal, advanced cathode, liquid electrolyte, first generation of solid state battery |
| 2035 | 350 - 400 | Li metal, all solid state |
| ???? | > 400 Wh/kg | Likely Li metal, all solid state |
| ????? | > 500 Wh/kg | New materials, chemistries, concepts |

Assumptions: Current pace of development, commercial ready for large pack sizes, adequate cycle life

# NASA – DOE Workshop

December 2019, Hosted by Argonne National Laboratory

# NASA-DOE Workshop on Batteries for Electric Aviation - December 2019

- Based on the success of the first workshop hosted by GRC in 2017
- Organized by NASA and DOE Vehicles Technology Office, hosted by Argonne National Laboratory
- Attended by ~100 participants (NASA, DOE, national laboratories, aircraft and engine companies, automobile companies, battery manufacturers, academia)
- Highlighted differences between automobile and aircraft applications
- Identified opportunities for leveraging technologies being developed by DOE,  national labs, and industry
- Identified technologies and research/testing effort that will be needed for electric aviation beyond the current investment by DOE and industry

# Strategy for Addressing Electric Aviation Battery Challenges

- Current investment by DOE and industry will lead to batteries with 300 – 350 Wh/kg pack specific energy
  - Can enable all-electric eVTOL, commuter aircraft and hybrid-electric 50 passenger regional aircraft

- For some missions, batteries with optimized specific energy and power density need to be developed

- Achieving pack specific energy of 400 – 500 Wh/kg will require augmented effort beyond the current level of investment, particularly development and maturation of of all solid state and Li-S batteries including manufacturing technologies for fabricating large size solid state battery stacks

- Achieving pack specific energy greater than 500 Wh/kg will require new paradigms

# Differences Between Automobile and Aircraft

| | Electric Vehicle | Electric Aviation |
|---|---|---|
| **Mission profiles** | Well established using decades of analysis by DOE and USABC and translated from system to material scale | Needs to be codified and different battery chemistries need to be evaluated under these conditions |
| **Discharge rates** | Short pulses (2-10s) at moderate rates until 80% DOD | 2-3x higher (could be higher) rate than EVs sustained for 90s at high DOD for eVTOL's |
| **Operating temperature** | Need to operate at low temperatures, below 0C | Higher temperature desirable for eVTOL, allowing exploration of high temperature batteries (e.g., solid polymer, ceramic-polymer electrolytes) |
| **Cycle and Calendar life** | 1000 cycles with a calendar life of 8 years | Calendar life requirements are only 1-2 years but requires 1000-4000 cycles. Limited calendar life may allow use of systems such as Si anodes |
| **Battery swapping** | Attempted in the small scale, but limited by infrastructure cost and lack of standardization | Opportunity to build the aviation market with swapping in mind. However, challenges related to safety need to be solved |
| **Novel packaging to maximize energy density at the module** | Approximately 50% loss from moving to cell to module | Opportunities for improving packaging and integrating batteries into vehicle components may offer new opportunities. |
| **Energy density enhancements** | 235 $Wh/kg_{pack}$ in near-term. Further increase to 300 $Wh/kg_{pack}$ likely to extend range. Focus will be cost reduction after that. | Near term concepts can leverage current battery R&D pipeline. However, 737-class aircraft require >700 $Wh/kg_{pack}$, requiring new approaches |

# Battery Needs for Electric Aviation (Beyond Current DOE and Industry Investment)

| | Technology Needs |
|---|---|
| **System Level Modeling** | Identify reference mission for each aircraft class and conduct system analysis to pinpoint opportunities as a function of battery capabilities |
| | Link aircraft propulsion models to battery performance and life models to better define interaction of batteries under aviation conditions |
| **Next Gen Li – Performance and Safety** | Evaluate high discharge operation of Li-ion cells, especially focused on eVTOL applications and develop possible solutions (e.g., new chemistries with high specific energy and power density capability or new thermal management solutions) |
| | Evaluate performance of next generation Li-ion (silicon, high Ni NMC) under aviation conditions and examine/model failure modes and safety aspects |
| **Packaging and Integration** | Develop efficient designs to package cells to modules and packs taking advantage of emerging approaches such as 3-D printing, bipolar designs and multifunctionality |
| **Beyond Next Gen Li** | Augment R&D on all solid state batteries to examine new designs, manufacturing approaches, high temperature operations, etc. |
| | Develop chemistries with 3-5X higher specific energy, including evaluating the possibility of enabling high energy primary batteries, sulfur-based chemistries, and hydrogen carriers with the aim of providing solutions for large regional and 737-class aircraft |

# Concluding Thoughts on Battery Technology

- Pack specific energy of 300 Wh/kg is achievable within reasonable timeframe
- Pack specific energy of 400 Wh/kg will probably require maturation of all solid state technology or Li-S with liquid electrolyte
- No clear path for achieving pack specific energy greater than 500 Wh/kg; will require new paradigms
- Performance, safety,  and life of developmental batteries under aircraft operating conditions need to be evaluated, particularly under high C-rating operation
- Opportunities for better packaging and integration with aircraft

# Questions?

- **Submit questions to grc2.cnf.io**